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FLIGHT INVESTIGATION OF APPROACH AND FLARE FROM SIMULATED BREAKOUT ALTITUDE OF A SUBSONIC JET TRANSPORT AND COMPARISON WITH ANALYTICAL MODELS

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16. Abstract

Satisfactory and optimum flare windows are defined from pilot ratings and comments. Maximum flare normal accelerations, touchdown rates of sink, and total landing maneuver time increments are summarized as a function of approach airspeed margin (with respect to reference airspeed) and flare initiation altitude. The effects of two thrust management techniques are investigated. Comparisons are made with predictions from three analytical models and the results of a simulator study.

The approach speed margin was found to have a greater influence on the flare initiation altitude than the absolute airspeed. The optimum airspeed was between the reference airspeed and the reference airspeed plus 10 knots. The optimum flare initiation altitude range for unrestricted landings was from 11 meters to 20 meters (36 feet to 66 feet), and the landing time in the optimum window was 8 seconds. The duration of the landing maneuver increased with increasing flare initiation altitude and with increasing speed margins on the approach. This trend contrasted with the decreasing maneuver duration with increasing absolute airspeed predicted by two analytical models. This discrepancy was attributed to differences in landing techniques used by the pilots in the various parts of the approach airspeed and breakout altitude envelope.

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INTRODUCTION

The approach and landing is considered the most demanding task in transport aircraft operations. The critical nature of the task is substantiated by accident statistics for commercial transports (refs. 1 and 2). The National Aeronautics and Space Administration, the Federal Aviation Administration, and many other agencies are studying the approach and landing flight region to define problem areas, certification methods, and approach control requirements in an effort to reduce the difficulty of the task. These investigations include the use of analytical models (refs. 3 to 5) and statistical (refs. 6 and 7) and simulator studies of operational approach and landing procedures.

The analytical study of reference 3 and unpublished simulator data obtained by C. T. Jackson, Jr., and G. E. Cooper at the NASA Ames Research Center indicate that many factors affect the approach airspeed, the flare initiation altitude, and the flare technique, which, in turn, affect passenger comfort, airplane touchdown conditions, landing time, and runway distance. These studies suggest that the approach airspeeds and flare initiation altitudes at which acceptable flares can be performed are limited for transport airplanes.

Although statistical studies show variations in certain parameters during normal operating procedures, they do not indicate the cause and effect of these variations or their impact on flight safety. Analytical models provide some insight into the limiting factors in the approach and landing maneuver and provide a first approximation of the acceptable ranges of these factors. They do not, however, provide any means of evaluating the effects of these factors on pilot technique. Simulators, on the other hand, include both aircraft and pilot dynamics and thus provide a more complete parametric evaluation of landing maneuvers. The difficulty of providing realistic visual and motion cues to a pilot for the landing task in ground-based simulators, however, generally requires flight verification of the results.

To evaluate the trends found in the analytical studies of references 3 to 5, and to expand on the statistical studies of references 6 and 7, the NASA Flight Research Center made a flight study of factors that affect the approach and landing task. A typical subsonic jet transport airplane was used to obtain data and to study the effects of approach airspeed, simulated breakout altitude, flare altitude, and thrust management on approach and flare performance and piloting technique. The results of this flight study are presented in this report and are compared with the simulator data and the predictions from the three analytical models.

SYMBOLS

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U.S. Customary Units. The measurements were taken in U.S. Customary Units. Factors relating the two systems are presented in reference 8.

a_n	normal acceleration at the airplane center of gravity, g
Δa_n	incremental normal acceleration at the airplane center of gravity, g
E_v	vertical component of specific energy, m (ft)
h_o	altitude above the ground at flare initiation, m (ft)
R_T	rate of sink at the end of flare, m/sec (ft/sec)
t_l	landing time increment, sec
V	indicated airspeed, knots
V_R	reference indicated airspeed, knots
V_s	certified stall indicated airspeed, knots

Subscript:

max	maximum

DESCRIPTION OF TEST AIRPLANE

The airplane used in this study was a swept-wing, subsonic, jet transport with a maximum gross weight of 1125 kilonewtons (253,000 pounds). It was powered by four turbojet, axial-flow, aft-fan engines with a combined takeoff thrust rating of approximately 290 kilonewtons (64,000 pounds). The wings had full-span Krueger flaps on the leading edge and partial-span, double-slotted Fowler flaps on the trailing edge. Conventional ailerons and spoilers provided lateral control, and a rudder provided directional control. An all-movable horizontal stabilizer provided longitudinal trim, and tab-controlled elevators provided longitudinal control. The stabilizer was hydraulically actuated, although electrical and mechanical backup systems were included. The elevators were controlled through the servo action of tabs on the trailing edge; the tabs were mechanically actuated by control column position.

A three-view drawing of the airplane is shown in figure 1, and pertinent physical dimensions are listed in table 1. Additional information on the control system, stability and control characteristics, and lateral handling qualities is included in references 9 to 11.

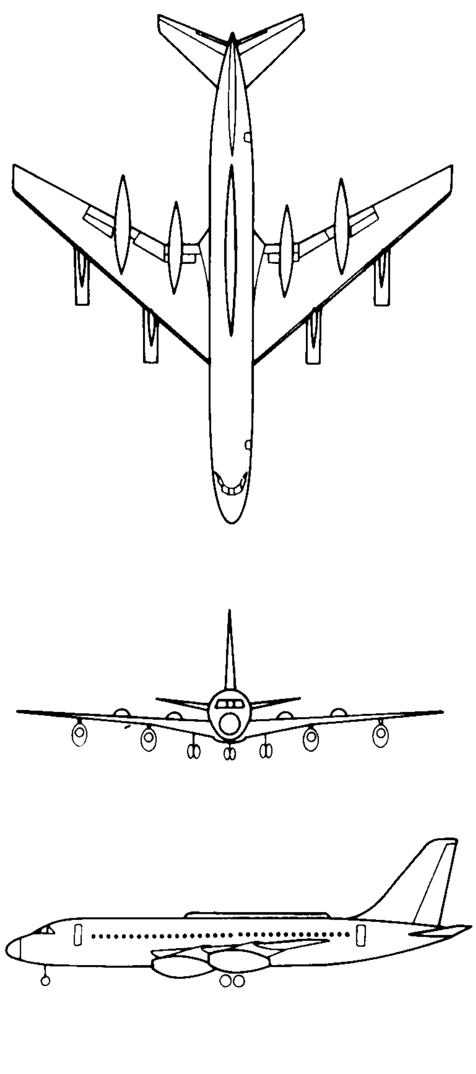


Figure 1. Three-view drawing of test airplane.

TABLE 1.—PERTINENT PHYSICAL CHARACTERISTICS OF THE TEST AIRPLANE

Fuselage —	
Maximum width, m (ft)	3.51 (11.50)
Maximum height, m (ft)	3.78 (12.42)
Length, m (ft)	42.60 (139.75)
Wing —	
Incidence (root), deg	4
Aerodynamic span, m (ft)	36.58 (120.0)
Area, m^2 (ft^2)	209 (2250)
Root chord, m (ft)	8.25 (27.06)
Tip chord, m (ft)	2.69 (8.83)
Mean aerodynamic chord, m (ft)	6.34 (20.81)
Dihedral, deg	7
Aspect ratio	6.2
Leading-edge sweep, deg	39
Horizontal stabilizer —	
Area, m^2 (ft^2)	39.6 (426.55)
Dihedral, deg	7.5
Leading-edge sweep, deg	41
Span, m (ft)	11.80 (38.74)
Aspect ratio	3.52
Vertical tail —	
Area, m^2 (ft^2)	27.4 (295)
Sweep at 30-percent chord, deg	35
Span, m (ft)	6.45 (21.17)
Aspect ratio	1.52
Aileron —	
Area, m^2 (ft^2)	2.78 (29.97)
Span, m (ft)	2.93 (9.62)
Maximum travel, deg	±15
Inboard spoiler —	
Area, m^2 (ft^2)	1.65 (17.8)
Mean aerodynamic chord, m (ft)	0.85 (2.8)
Maximum travel, deg	75
Outboard spoiler —	
Area, m^2 (ft^2)	3.86 (41.51)
Mean aerodynamic chord, m (ft)	0.95 (3.11)
Maximum travel, deg	60

INSTRUMENTATION

The test instrumentation consisted of transducers, signal-conditioning units, and three 26-channel oscillographic recorders. The data were recorded on sensitized paper and correlated by a common timer at $\frac{1}{10}$-second intervals. Air data were obtained with a NACA A-6-type airspeed head (ref. 12) mounted on a boom ahead of the nose of the airplane. The data were not corrected for flight-induced errors; therefore, all parameters are presented as indicated data. The results of an instrumentation error analysis are presented in table 2.

TABLE 2.— INSTRUMENTATION ACCURACY

Parameter	Range	Total error
Elevator, deg —		
Left	12.1 to -25.2	±1.8
Right	11.4 to -25.7	±1.7
Rudder, deg	±25.1	±1.4
Aileron, deg —		
Left	14.6 to -15	±1.4
Right	15.1 to -16	±1.5
Spoiler, deg —		
Left outboard	59.4 to 0	±2.6
Left inboard	68 to 0	±2.9
Right outboard	58.3 to 0	±2.6
Right inboard	73.2 to 0	±3.1
Static pressure, N/m^2 (lb/ft^2)	15,082 (315)	±891 (±18.6)
Total pressure, N/m^2 (lb/ft^2)	3400 (71)	±168 (±3.5)
Angle of attack, deg	35 to -15	±2.1
Angle of sideslip, deg	±16	±1.4
Pitch angle, deg	40 to -20	±2.7
Roll angle, deg	±20	±1.9
Pitch rate, deg/sec	±10	±0.9
Roll rate, deg/sec	±20	±1.8
Yaw rate, deg/sec	±10	±0.9
Acceleration at center of gravity, g —		
Normal	2.5 to 0	±0.11
Transverse	±0.5	±0.04
Radio altitude, m (ft)	0 to 76 (250)	±3.87 (±12.7)
Elevator column force, N (lb)	±667 (±150)	±34 (±7.6)

Pilot comments were tape recorded after each maneuver.

The basic cockpit instrumentation display was modified to provide indicators of test parameters such as angle of attack, angle of sideslip, and radio altitude.

FLIGHT PROGRAM

The flight program consisted of 71 approaches and landings made by three research pilots with a broad range of experience that included transport types of operations. For each approach and landing the pilots were asked to comment on the effects of approach airspeed, breakout altitude, longitudinal control for flaring, and other pertinent characteristics that influenced the maneuver. A pilot rating based on the revised Cooper scale shown in table 3 was given for most of the maneuvers.

TABLE 3.—PILOT RATING SCALE

<table>
<tr><td rowspan="9">Controllable

Capable of being controlled or managed in context of mission, with available pilot attention.</td><td rowspan="6">Acceptable

May have deficiencies which warrant improvement but adequate for mission. Pilot compensation, if required to achieve acceptable performance, is feasible.</td><td rowspan="3">Satisfactory

Meets all requirements and expectations. Good enough without improvement. Clearly adequate for mission.</td><td>Excellent, highly desirable.</td><td>1</td></tr>
<tr><td>Good, pleasant, well behaved.</td><td>2</td></tr>
<tr><td>Fair, some mildly unpleasant characteristics. Good enough for mission without improvement.</td><td>3</td></tr>
<tr><td rowspan="3">Unsatisfactory

Reluctantly acceptable deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.</td><td>Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.</td><td>4</td></tr>
<tr><td>Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.</td><td>5</td></tr>
<tr><td>Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.</td><td>6</td></tr>
<tr><td rowspan="3">Unacceptable

Deficiencies which require mandatory improvement. Inadequate performance for mission even with maximum feasible pilot compensation.</td><td rowspan="3"></td><td>Major deficiencies which require mandatory improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.</td><td>7</td></tr>
<tr><td>Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.</td><td>8</td></tr>
<tr><td>Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.</td><td>9</td></tr>
<tr><td colspan="3">Uncontrollable

Control will be lost during some portion of mission.</td><td>Uncontrollable in mission.</td><td>10</td></tr>
</table>

Approaches were made to the 4600-meter (15,000-foot) main runway at Edwards Air Force Base, Calif., which has an elevation of 702 meters (2302 feet) and a positive slope of 0.14 percent. At the time of the tests, the 3° ILS glide-slope intersection was 730 meters (2400 feet) from the approach end of the runway. All tests were performed under ideal weather conditions with the airplane in the landing configuration, that is, with the landing gear down, the Krueger flaps extended, and the Fowler flaps at 50°.

On all test maneuvers the ILS glide slope was intercepted 600 meters (2000 feet) above ground level and the landing approach was made at test airspeed. The piloting task required flying an ILS approach precisely to a predetermined breakout altitude and then transitioning to visual flight to perform a landing maneuver commensurate with transport operations. Although the pilot's vision was not limited to the cockpit area, the task of flying a precise ILS approach provided enough restriction to simulate reduced visibility conditions. The breakout altitude was signaled by a light mounted on a glare shield in front of the pilot; the light was actuated by the radio altimeter. For each approach the altitude for breakout was set by the safety pilot but was unknown to the test pilot. On each maneuver, thrust was managed either as desired by the pilot or as a thrust cut at the time of the breakout signal. The thrust-cut maneuver was included because it is typical of maneuvers performed during tests for certification of landing distances (ref. 13). After touchdown the normal landing procedure was continued through spoiler-brake extension and activation of the thrust-reverser doors. The maneuver was terminated when all thrust-reverser doors were activated and the nosewheel was on the ground. The basic segments of the approach and landing maneuver are illustrated in figure 2.

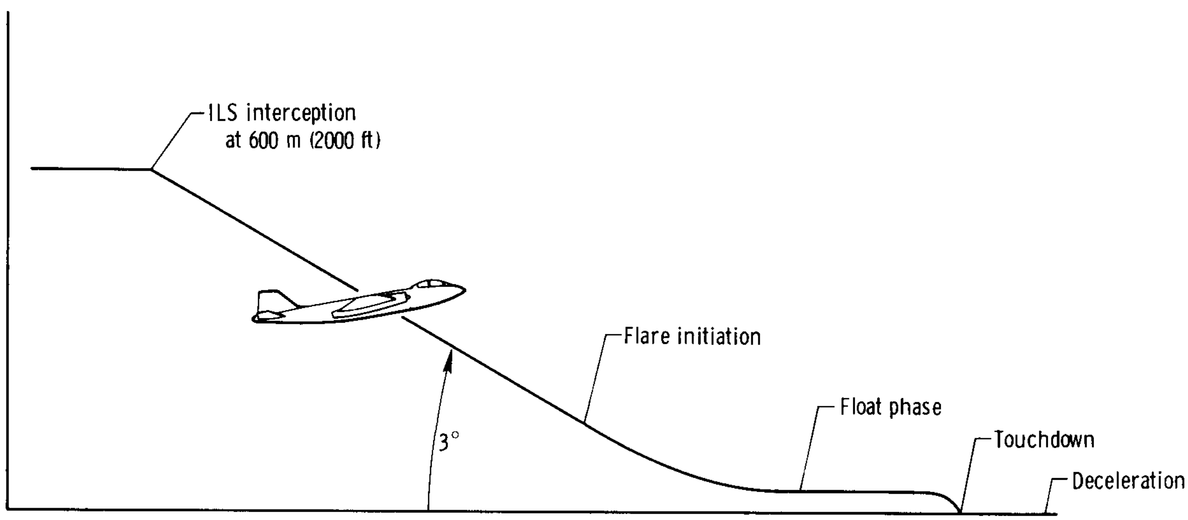
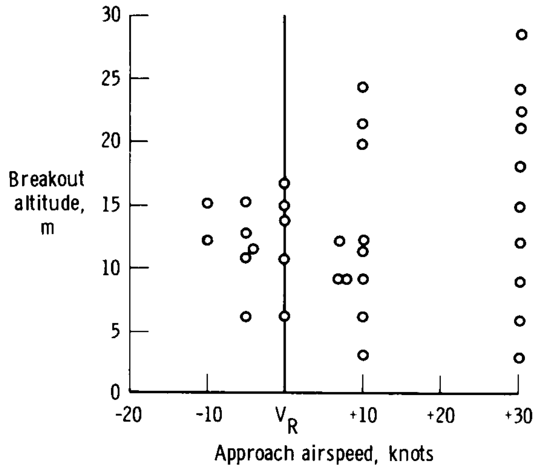


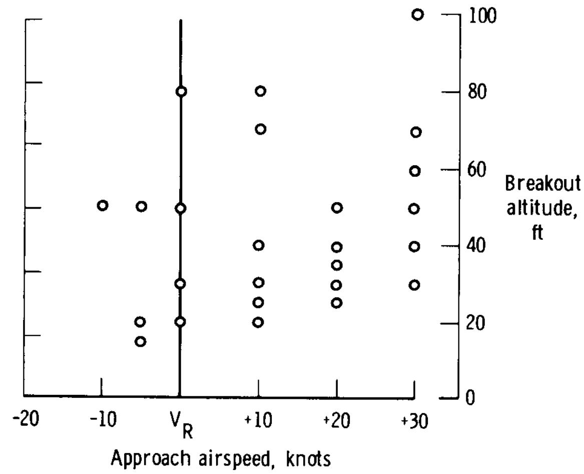
Figure 2. Basic segments of the approach and landing maneuver.

Early in the program it was found that the pilot instinctively pulled back on the controls during the transition from instrument to visual reference. Because of this tendency, an oral warning was given 2 to 3 seconds before breakout to allow the pilot to visually assess the situation before performing the landing maneuver.

Approach airspeeds were based on the reference airspeed, V_R (defined as 1.3 times the certified stall speed, V_s), and ranged from V_R - 10 knots to V_R + 30 knots. Reference airspeeds varied from 121 knots at an airplane gross weight of 560 kilonewtons (126,000 pounds) to 155 knots at a gross weight of 872 kilonewtons (196,000 pounds). Corresponding approach airspeeds were from 118 knots to 176 knots. The breakout altitude was based on the height of the main gear above ground level as measured by the radio altimeter and ranged from 3 meters (10 feet) to 30 meters (100 feet). Figure 3 shows the approach airspeeds and breakout altitudes investigated.



(a) *Thrust as desired.*



(b) *Thrust cut at breakout.*

Figure 3. Approach airspeeds and breakout altitudes investigated.

To facilitate handling the results of this flight study, approach airspeeds were grouped into three categories: slow (V_R - 10 to V_R), intermediate (V_R to V_R + 20), and fast (V_R + 20 to V_R + 30). The breakout altitudes were also grouped into three categories: high, intermediate, and low. The absolute altitude for each category is based on pilot opinion and varies with the approach airspeed. Only the slow and fast approaches with high and low breakout altitudes are discussed in this section; typical time histories are included.

The lateral-directional characteristics of the test airplane were acceptable and had no significant influence on the landing maneuvers.

Slow Airspeed Characteristics

Approach phase.—Approaches made at airspeeds of V_R - 10 to V_R were considered to be too slow. The pilots commented that thrust adjustments required to maintain the desired airspeed increased the pilot's workload and thus degraded his ability to control the flightpath. In addition the resulting nose-high attitude (fig. 4) reduced the pilot's visibility and made it more difficult to judge altitude. Although the test airplane had adequate longitudinal control for all the test conditions, the reduction in control power at the lower velocities was noticeable—a factor which could be significant on other airplanes.

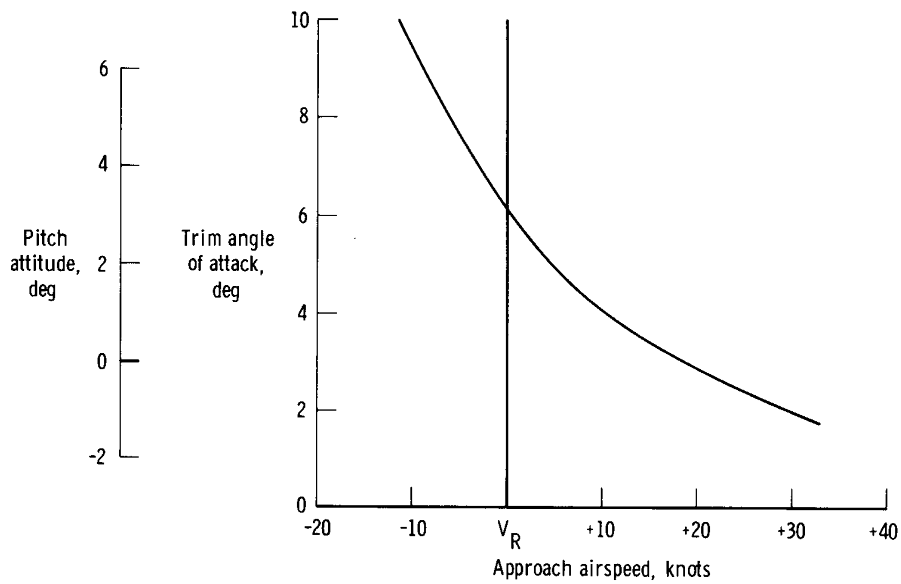


Figure 4. Variation of trim angle of attack and pitch attitude with approach airspeed.

Flare maneuver.—When a flare was attempted from a slow approach, the buffet-free maneuvering capability of the airplane was reduced and there was a possibility of the tail bumping the ground during touchdown. The pilots expressed concern about losing airspeed and getting into a situation in which the airplane would develop excessive sink rates and not have enough energy to perform the flare maneuver. To avoid further speed loss, the pilots performed the landing maneuver so that the float phase was minimized or eliminated. Touchdowns were often made at the point of maximum normal acceleration in the flare.

When thrust-as-desired landings were started at high breakout altitudes from slow approaches, airplane rotation and thrust reduction were delayed to a lower altitude. The thrust was often maintained at the approach level until touchdown occurred. In landings from a slow approach with the thrust cut (thrust retarded to idle) at breakout, the pilot either maintained the airplane attitude or allowed the nose to drop slightly to maintain airspeed, thus increasing the rate of sink. Pilot workload was highest in these maneuvers. The time history of a typical thrust-cut maneuver at V_R + 2 knots in which the breakout altitude was 24 meters (80 feet) is shown in figure 5. The thrust was cut near breakout, as shown by the drop in engine pressure ratio which lagged the throttle motion by approximately 1 second. However, the pilot did not initiate the flare until an altitude of 15 meters (50 feet) was reached and did not achieve positive normal acceleration until the altitude dropped to 6 meters (20 feet). At touchdown, the airspeed had decreased 13 knots from the approach airspeed; this loss was almost one-half the speed margin above stall.

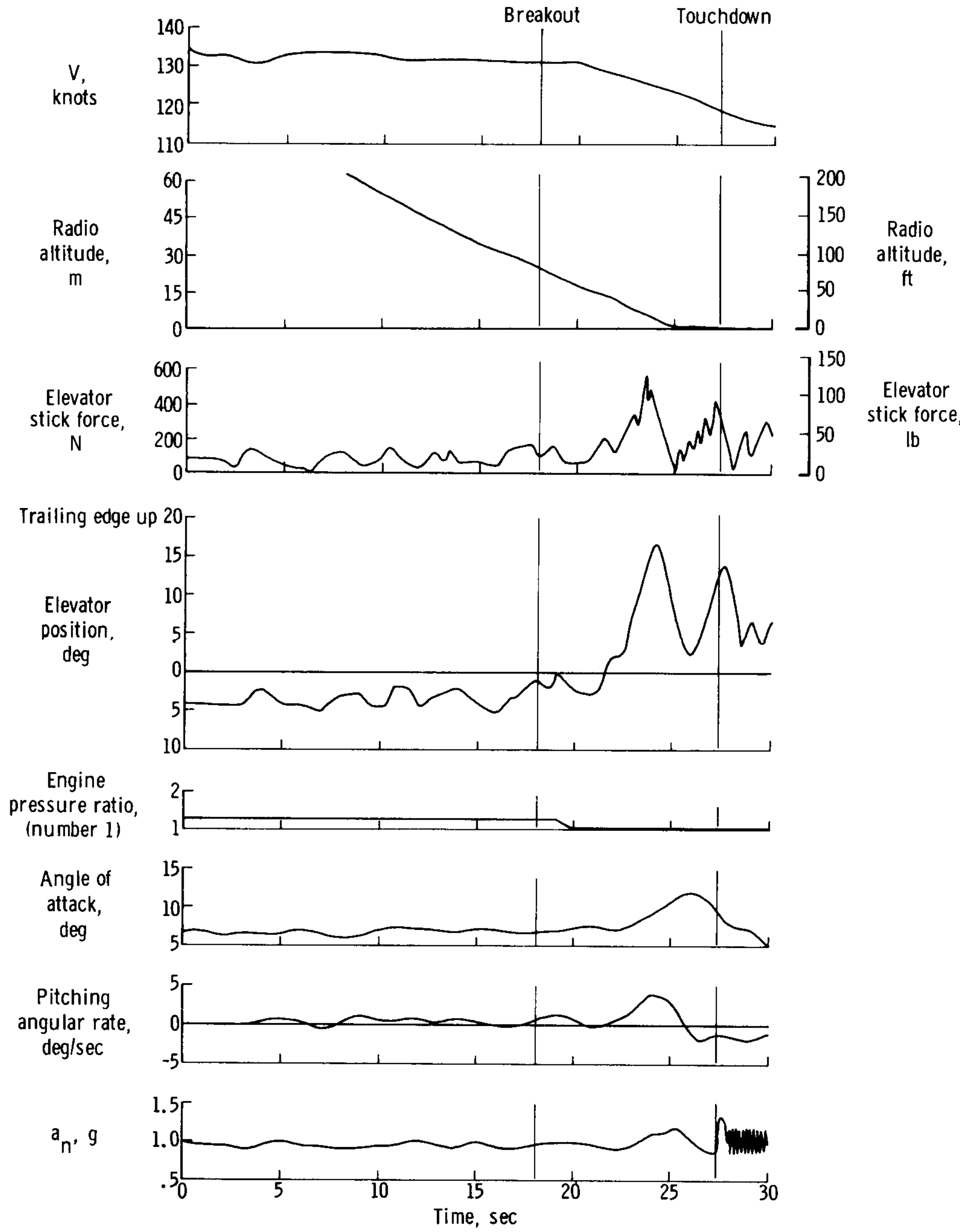
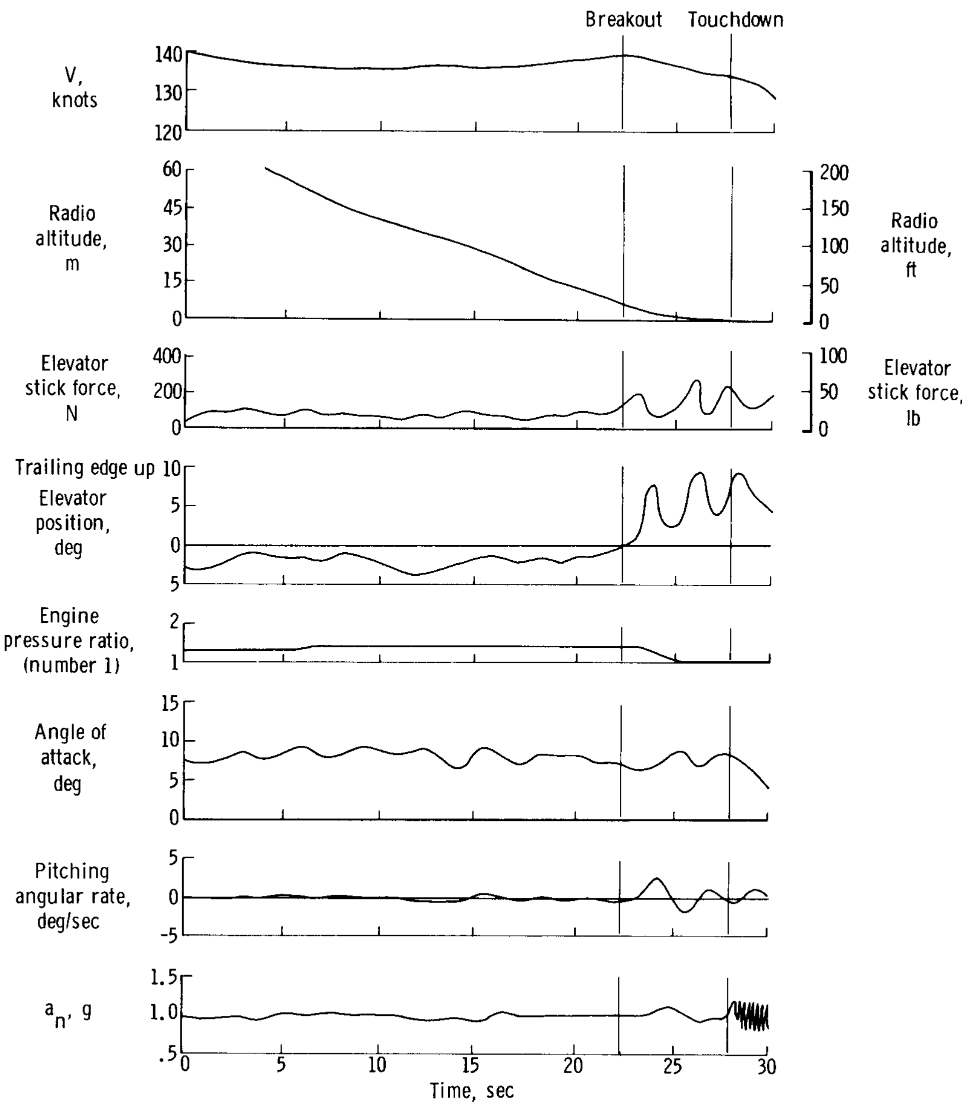


Figure 5. Time history of a slow approach with a high breakout altitude and thrust cut. V_R = 130 knots; gross weight = 647.6 kN (145,600 lb).

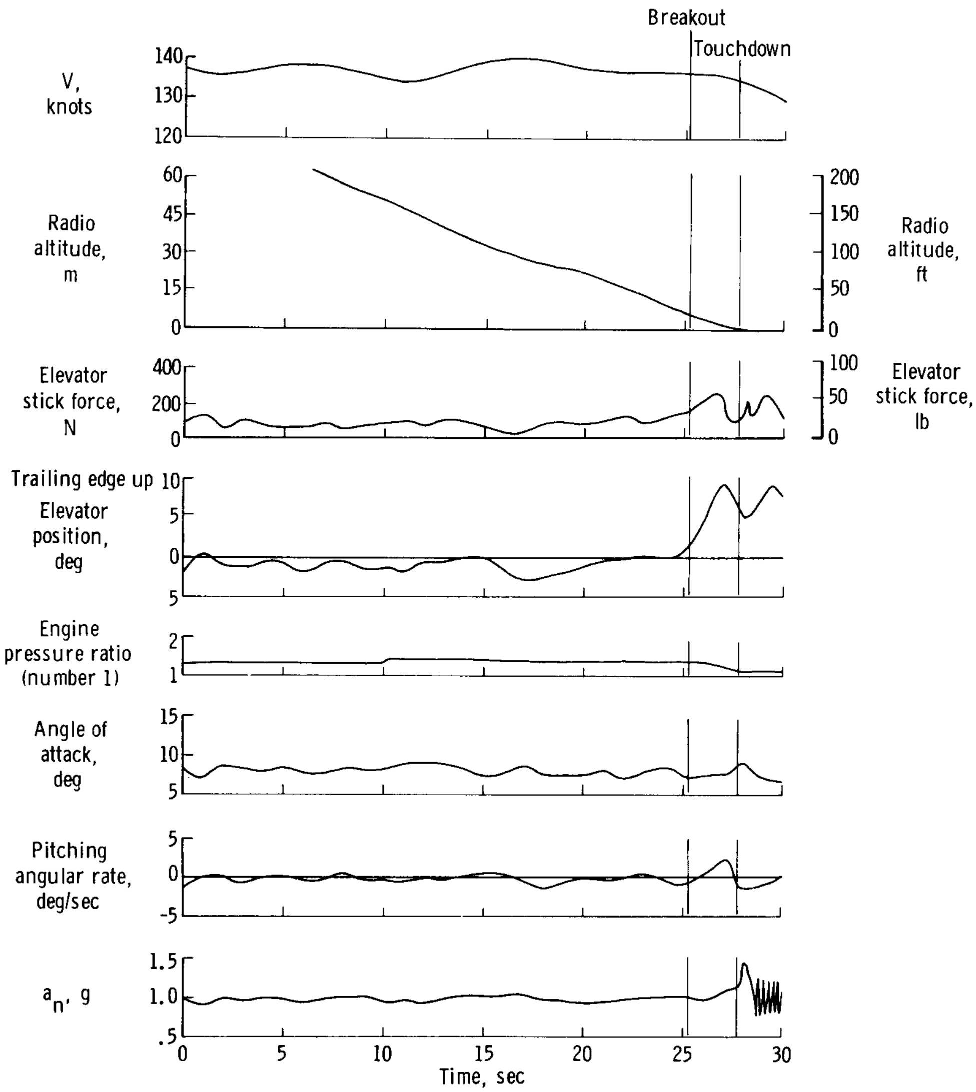
When a flare was attempted in a slow approach at low altitude, reduced control power and airplane longitudinal oscillations at flare initiation became of prime concern to the pilot. Figure 6(a) is a time history of a thrust-as-desired maneuver performed at V_R - 8 knots with a breakout altitude of 6 meters (20 feet). The maneuver was reasonably steady up to breakout where airplane rotation was started and the thrust gradually reduced. The flare was carried through to a smooth touchdown, although it was accompanied by some oscillations in angle of attack.



(a) Smooth landing. V_R = 148 knots; gross weight = 805.1 kN (181,000 lb).

Figure 6. Time history of a slow approach with a low breakout altitude and thrust as desired.

The time history shown in figure 6(b) is for a maneuver performed under essentially the same conditions as the maneuver of figure 6(a). The approach phase of this maneuver is somewhat more oscillatory in pitch, in that a nose-down rate of 1 degree per second occurred at flare initiation in contrast to a nose-down rate of 0.4 degree per second in figure 6(a). Although nose-up elevator was used earlier for the maneuver of figure 6(b) than for the maneuver of figure 6(a), the additional



(b) Hard landing. V_R = 147 knots; gross weight = 794.0 kN (178,500 lb).

Figure 6. Concluded.

nose-down pitch rate at flare initiation caused a slight decrease in normal acceleration that resulted in a hard landing. The rate of sink at touchdown for the maneuver of figure 6(b) was 2.0 meters per second (6.7 feet per second) in contrast to

0.2 meter per second (0.6 foot per second) for the maneuver of figure 6(a). The highest rates of sink at touchdown were experienced at the slow approach speeds and showed no trend with the breakout or flare initiation altitude.

Although there are many causes of aircraft oscillations, only thrust modulation and ground effect were found to be significant in this study. When the pilot had to manipulate thrust on approach, not only was his workload increased, but each thrust adjustment caused a pitching transient which required correction. This was one of the principal reasons why the pilots disliked the thrust-cut maneuver. The pitching oscillations were not caused by ground effect, but rather by the pilot's attempt to control the airplane while it was experiencing ground effect. These pitching oscillations resulted in wide variations in pilot comments and ratings for low-altitude flares at slow-approach airspeeds.

Fast Airspeed Characteristics

Approach phase.—Although the fast approach (V_R + 20 knots to V_R + 30 knots) characteristics were generally satisfactory, altitude judgment, airplane attitude, and an excess of energy were of concern to the pilot. Altitude judgment was difficult because of the higher rates of sink and the nose-down attitude at these higher speeds (fig. 4), which caused the closure rate to appear to be greater than for the same rate of sink with normal airplane attitudes associated with higher gross weights. All three pilots commented that V_R + 30 knots was a maximum acceptable approach velocity.

Flare maneuver.—For fast approaches with a high-altitude breakout and thrust as desired, the pilot wished to reduce the airplane velocity before touchdown. Thus he generally reduced the thrust near breakout, but at a slower rate than with a thrust cut. Flare initiation control inputs were delayed to lower altitudes to avoid long flare and float distances and resulted in touchdown airspeeds faster than the reference airspeed. Float phases of 4 to 6 seconds duration resulted from the pilots "feeling" for the runway at this high energy condition.

Low-altitude breakouts from fast approaches were considered unsatisfactory, approaching conditions for which a pilot rating of unacceptable would be given. The fast-approach airspeed coupled with the nose-down attitude tended to increase pilot concern as the breakout altitude was decreased. At these velocities and flare altitudes the pilots used rapid control inputs to avoid the possibility of a hard or nosewheel-first landing. However, because of the longitudinal control available, a flare was made with an approach velocity of V_R + 30 knots and a flare initiation altitude of 5 meters (18 feet). The time history of this maneuver is shown in figure 7. The pilot overcompensated for ground effect at an altitude of approximately 15 meters (50 feet) and then initiated the flare at 5 meters (18 feet). Thrust was applied as desired in this maneuver and was cut shortly after the flare was started. The airplane came within 1 meter (3 feet) of the ground and then floated for approximately 6 seconds before touching down. There were no significant differences between the thrust-as-desired and the thrust-cut maneuvers performed during fast approaches.

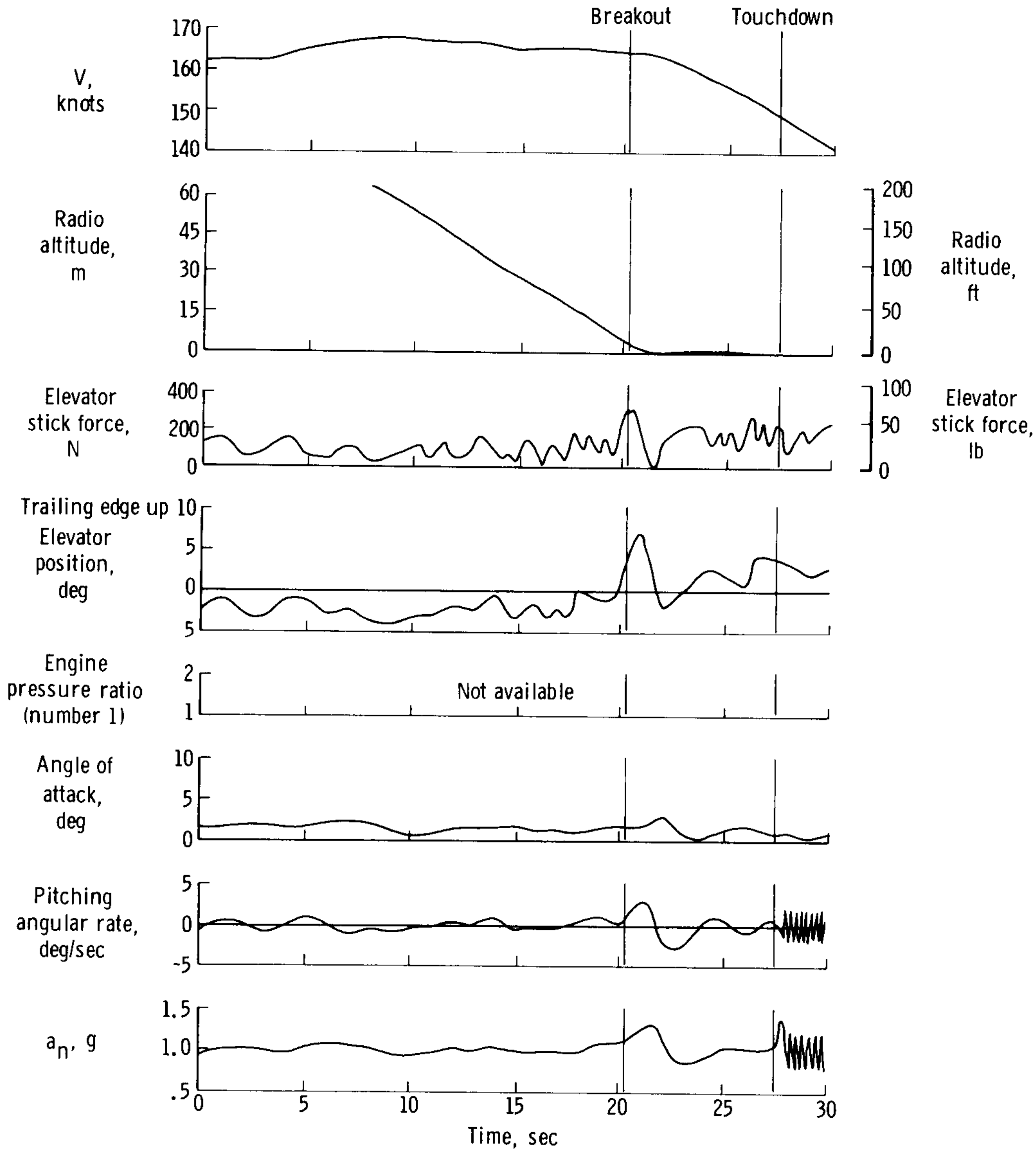


Figure 7. Time history of a fast approach with a low breakout altitude and thrust as desired. V_R = 138 knots; gross weight = 714.3 kN (160,600 lb).

Landing Maneuver Time

The time used to perform a landing maneuver (flare initiation to touchdown) is a measure of maneuver performance as well as a means of estimating the runway distance covered before deceleration devices can be used. A flare maneuver begins when a pilot initiates such action as reducing thrust or rotating an airplane to depart from a steady-state approach. The landing times (flare initiation to touchdown) for all the maneuvers in this flight program are summarized in figure 8. This figure shows fairings that were derived by least-squares curve fitting and linearization, and all the data that fall within ±0.5 second of these times. Variations in pilot technique and the limited amount of data available masked any differences in landing times between the thrust-as-desired and the thrust-cut maneuvers.

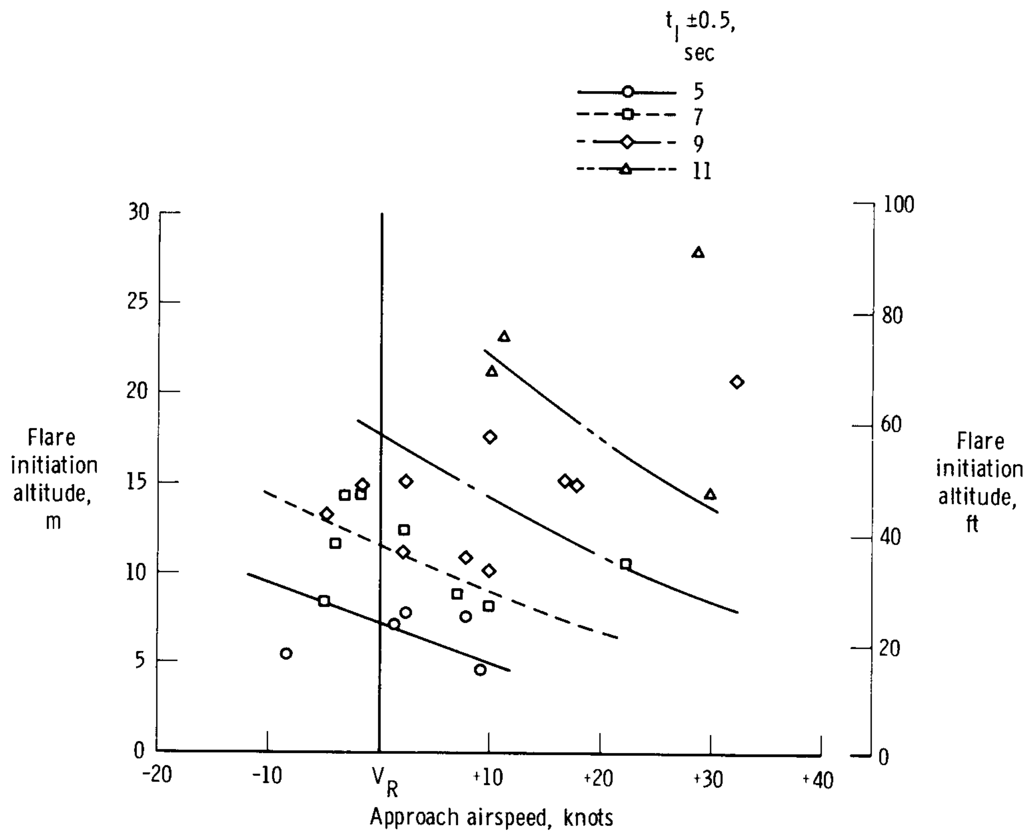


Figure 8. Summary of landing times from flare initiation to touchdown.

As shown in the figure, the landing time increment increased at constant approach airspeed with increasing flare initiation altitude and at constant flare altitude with increasing approach airspeed. The increase in landing time with increasing approach airspeed is attributed in part to the longer float time associated with the higher kinetic energy.

Touchdown Rate of Sink

The rates of sink at touchdown experienced in this program are summarized in figure 9. The higher rates of sink at touchdown were at the slow approach airspeeds, and most were less than 1 meter per second (3 feet per second). As discussed earlier, these data showed no effects of thrust management technique or flare initiation altitude.

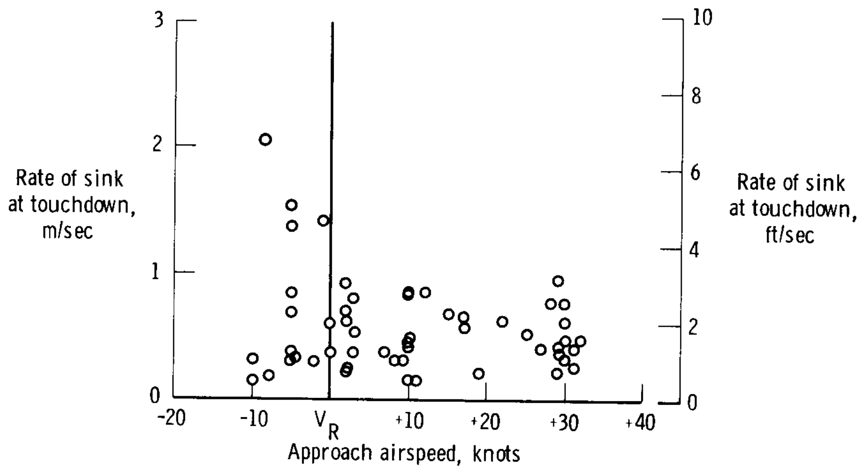


Figure 9. Summary of rates of sink at touchdown.

Flare-Maneuver Normal Acceleration

Figure 10 summarizes the maximum normal accelerations experienced during the thrust-cut flares as a function of breakout altitude and approach airspeed. As expected, the highest accelerations were experienced in the fast approach, low-altitude maneuvers. The increase in acceleration experienced at the higher breakout altitudes was caused by the delayed flare used by the pilots to avoid excessive speed loss. This technique is illustrated in the time history of figure 5. The data for the thrust-as-desired maneuvers were of the same level as those shown in figure 10, but did not show distinguishable trends.

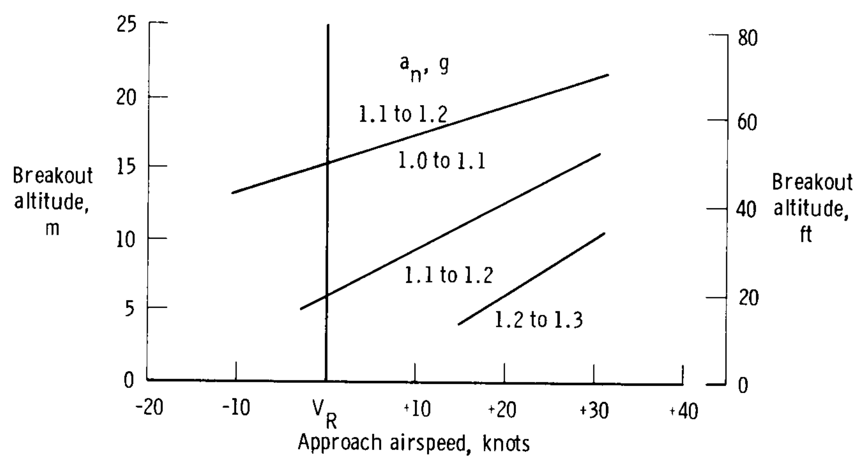


Figure 10. Summary of maximum normal accelerations experienced during thrust-cut flares.

Pilot Comments and Ratings

Pilot comments indicated that each part of the flare envelope required different approach and flare techniques and involved different airplane characteristics and hazards. These comments also indicated that the pilot's opinion of the acceptability of any breakout altitude was influenced more by the approach speed margin based on the reference airspeed than by the absolute airspeed. Table 4 summarizes the pilot comments about the approach airspeed and the flare altitude. More detailed pilot comments are presented in the appendix.

TABLE 4.— SUMMARY OF PILOT COMMENTS

	Slow approach	Fast approach
High flare altitude	Excessive speed bleed off may require added thrust or pitch down maneuver	Tendency to float and use excessive distance to touchdown
Low flare altitude	Reduced longitudinal response Danger of tail bumping ground	Pilot rushed; rapid inputs High closure rate Danger of nosewheel-first landing
General	Required thrust adjustments increase pilot workload Reduced visibility Close to buffet onset	High landing speeds Feeling for runway Excessive energy

A summary of the pilot ratings for 40 thrust-as-desired maneuvers, expressed as a function of breakout altitude and approach airspeed, is shown in figure 11.

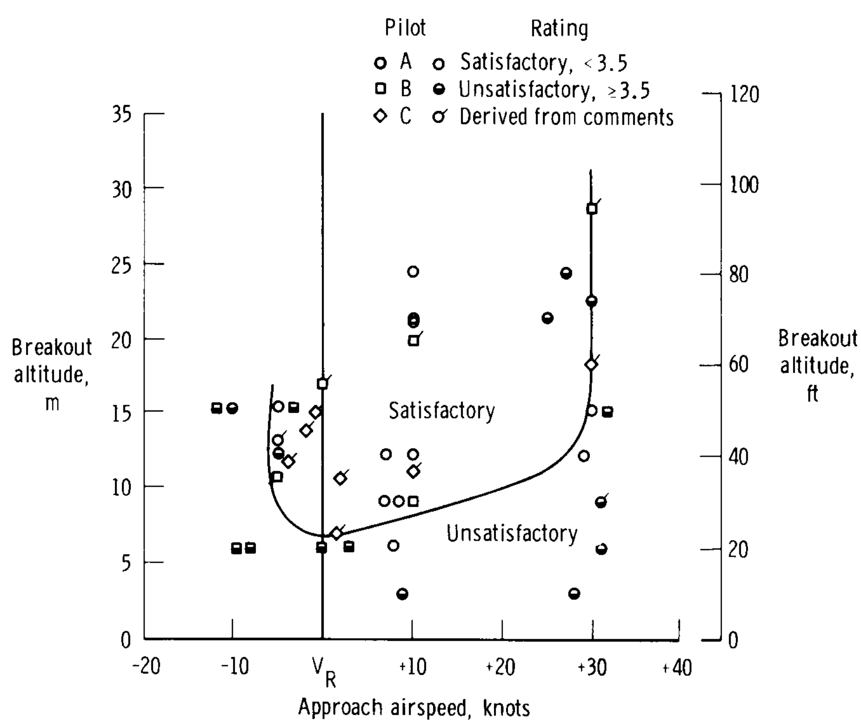


Figure 11. Summary of pilot ratings for thrust-as-desired maneuvers.

The flagged symbols designate maneuvers for which pilot ratings were not given. The satisfactory/unsatisfactory ratings for these maneuvers were determined from the pilots' taped comments. (See appendix.) The boundary is an approximate separation of satisfactory and unsatisfactory ratings (PR = 3.5) and outlines the breakout window for satisfactory landing maneuvers. The tape-recorded pilot comments as well as the pilot ratings were used to define the boundary, which has no upper limit because a high-altitude breakout with thrust as desired presented no problems to the pilot. Flare initiation was simply delayed until a lower altitude was reached.

Figure 12 summarizes the pilot ratings for 27 thrust-cut maneuvers and compares the PR = 3.5 boundary for the thrust-cut maneuvers with the thrust-as-desired boundary. These two boundaries are essentially identical at low altitudes because the pilots tended to cut the thrust at or near breakout even when this action was optional. On fast approaches the boundaries are the same because all pilots considered V_R + 30 knots to be the maximum satisfactory approach velocity. In the slow-approach, high-altitude region, the thrust-cut boundary is defined by the highest altitude at which the thrust could be cut without an excessive loss of energy before touchdown and, consequently, represents a more restrictive flare envelope than that for the thrust-as-desired maneuvers.

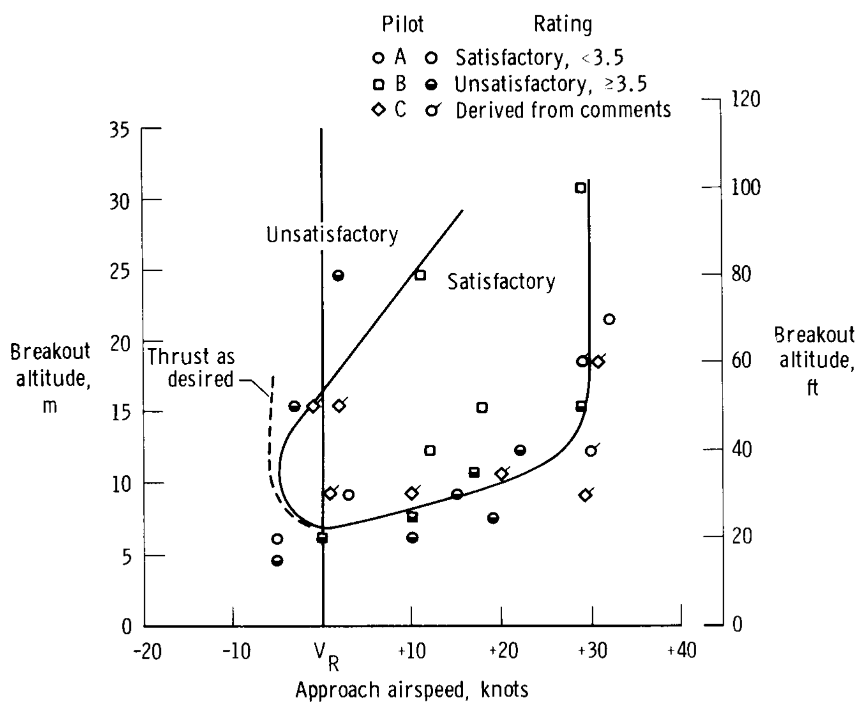


Figure 12. Summary of pilot ratings for thrust-cut maneuvers.

Optimum Flare Window

To define the best flare altitude for a given approach velocity and the optimum flare window with the thrust as desired, each pilot made approaches at several different airspeeds and selected what he considered to be the best altitude for flare.

In each of these maneuvers the pilots initiated the longitudinal rotation before reducing the thrust. The data for these maneuvers are summarized in figure 13. The optimum flare window lies between approach airspeeds of V_R and V_R + 10 knots and flare altitudes of 11 meters and 20 meters (36 feet and 66 feet). The best flare altitude at slow airspeeds is from 9 meters to 14 meters (30 feet to 45 feet); at fast airspeeds, it is from 15 meters to 27 meters (50 feet to 90 feet). The recommended approach velocity for commercial-carrier operations for the test airplane is V_R + 10 knots (ref. 14), which is within the optimum window of V_R to V_R + 10 knots. A comparison of the landing times in figure 8 with the optimum flare window shows that the optimum landing time is approximately 8 seconds.

The altitude range shown in figure 13 for flare initiation on fast approaches indicates that a wide range of pilot techniques can be used effectively. The reduced altitude range for flare initiation on slow approaches indicates a more difficult landing task with greater restrictions on pilot technique. The optimum flare window for the thrust-cut maneuvers was not determined.

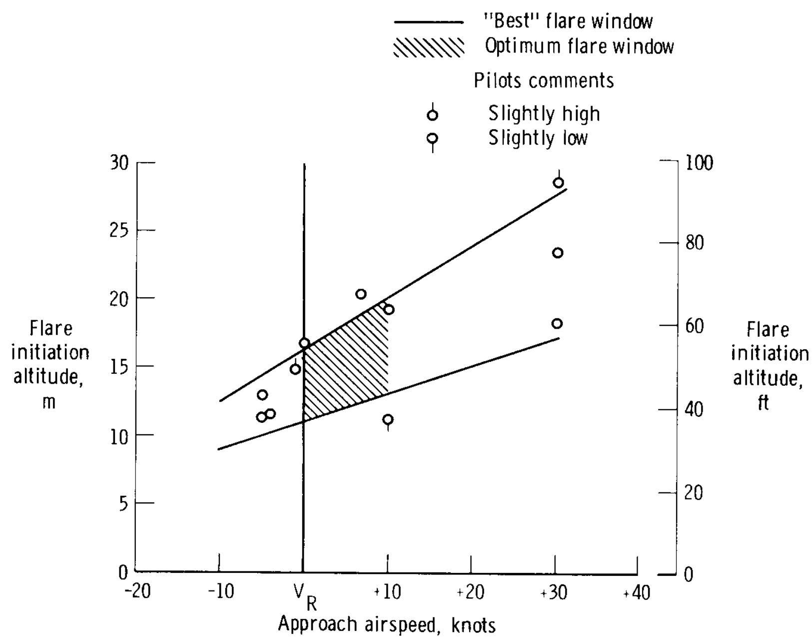


Figure 13. Optimum flare window for unrestricted landings.

Figure 14 compares the optimum flare window determined in this flight study with the results of the previously mentioned unpublished Ames simulator study made for a comparable transport airplane. The results are in general agreement. This limited comparison indicates that fixed-base simulators may be useful for defining flare initiation envelopes.

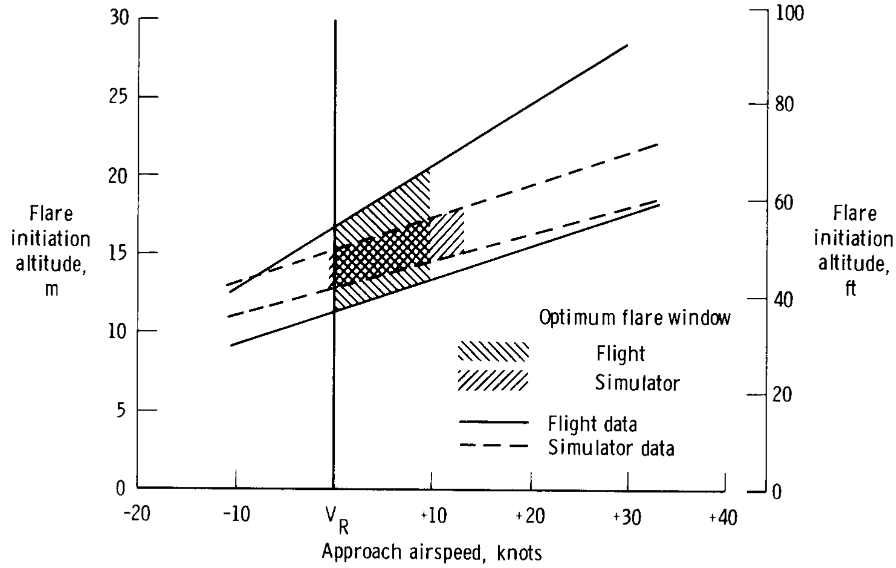


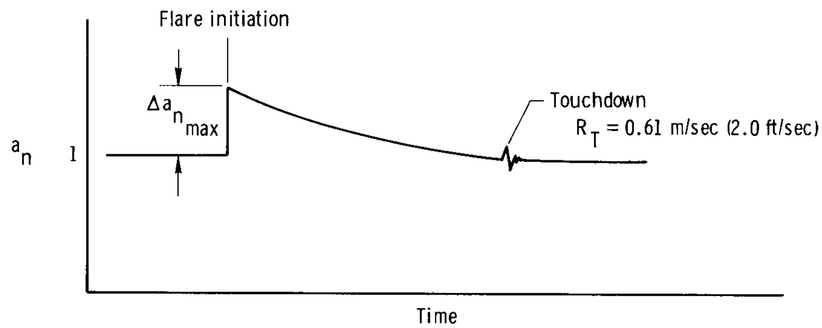
Figure 14. Comparison of optimum flare windows determined from flight and simulator studies.

Comparison of Flight Data With Theoretical Model Predictions

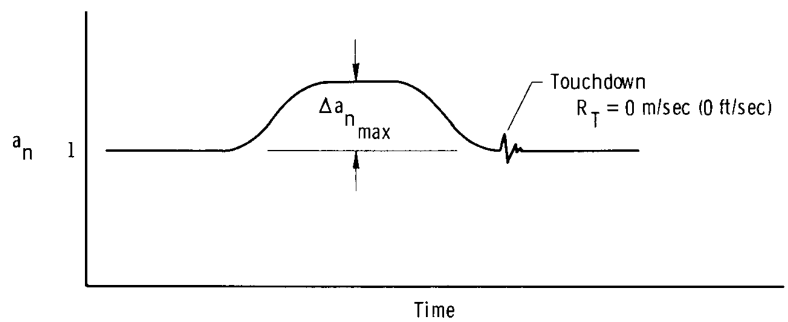
Attempts have been made to develop realistic mathematical models for the approach and landing of transport airplanes. These models have been used to perform parametric studies of such variables as approach airspeed, rate of sink, flare initiation altitude, normal acceleration, and flare duration (refs. 3 and 4) and to provide a means of computing approach airspeed (ref. 5). The results from such parametric studies have been used to evaluate the effects of these variables on touchdown speed and landing distance.

The assumptions on which the models of references 3 to 5 are based are summarized in figures 15(a) to 15(c) in terms of time histories of normal acceleration. For the model of reference 3 a step input of normal acceleration is assumed, followed by an exponential decay to touchdown with a rate of sink of 0.61 meter per second (2.0 feet per second). In the model of reference 4 a sinusoidal onset and decay with a period of constant normal acceleration between is assumed. Touchdown is assumed to occur at the time normal acceleration returns to 1g at zero rate of sink. In the model of reference 5 a step input of normal acceleration is applied and is held constant until zero rate of sink is achieved. This is followed by a float phase to touchdown.

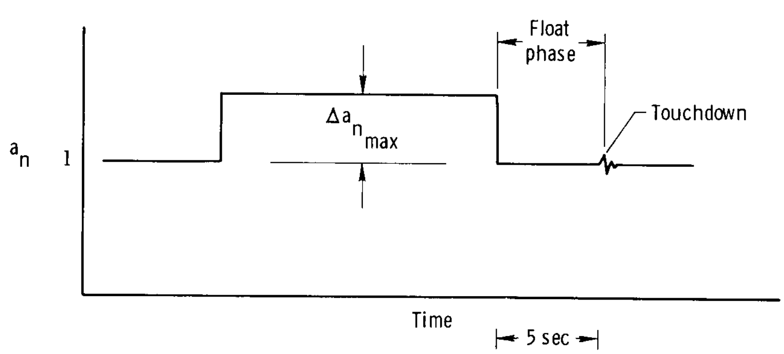
The models of references 3 and 4 are described by equations relating true airspeed, flare altitude, rate of sink, maximum normal acceleration, and flare time. It is assumed in these references that the pilots perform the landing maneuver defined by the equations at all approach airspeeds and flare initiation altitudes. The studies do not take into account the effect of speed margin with respect to reference airspeed or the various flare techniques used at different flare initiation altitudes.



(a) Reference 3 model.



(b) Reference 4 model.



(c) Reference 5 model.

Figure 15. Comparison of the normal acceleration characteristics assumed for the analytical models of references 3 to 5.

The primary purpose of the study of reference 5 is to compute an approach airspeed by using the aerodynamic characteristics of the airplane. Each phase of the flare maneuver is analyzed separately. Although allowing greater flexibility in assumptions than references 3 and 4, reference 5 considers only a typical approach and flare maneuver.

Comparisons are made in the following discussion between the flight data of this study and the predictions obtained by using the models of references 3 to 5. To compare data based on speed margin with respect to reference airspeed with data based on the absolute value of true airspeed, a nominal value of reference indicated airspeed of 135 knots was chosen. This airspeed is equivalent to 71 meters per second (235 feet per second) true airspeed at an altitude of 702 meters (2300 feet).

The maximum normal acceleration predicted by the method of reference 3 is compared with flight data for the thrust-cut maneuvers (fig. 10) in figure 16. The agreement of the data is good in the intermediate and low flare altitude ranges. The unusual "high dip" flare maneuver used by the pilots for the thrust-cut landings from high breakout altitudes, however, resulted in increased maneuver loads, as previously discussed.

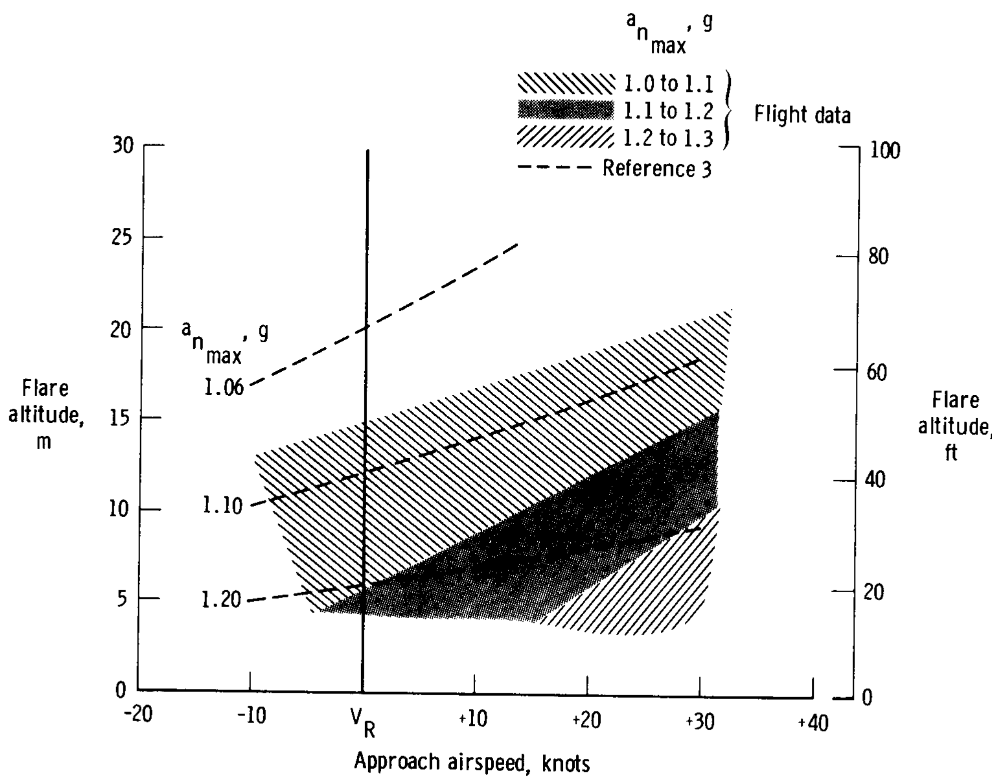


Figure 16. Comparison of the maximum normal acceleration during flare obtained from flight data with predictions from reference 3. V_R = 135 knots.

Figure 17 compares the landing time (from flare initiation to touchdown) obtained from flight data (fig. 10) with the landing time predicted from the model of reference 3. This figure shows that the model predicted a decreasing landing time increment from a given altitude as approach airspeed increased. This trend is opposite that of the flight data and is attributed to the different flare techniques used by the pilots in the various areas of the airspeed and altitude envelope. At the slower airspeeds the pilots tried to avoid losing additional airspeed and to touch down as quickly as possible. At the faster airspeeds the floating tendency of the airplane was a major contributor to the increased landing time. The line of agreement between the model and the flight data is near the optimum flare window of figure 13, which indicates that this model satisfactorily represents the landing maneuver for a typical jet transport under optimum conditions.

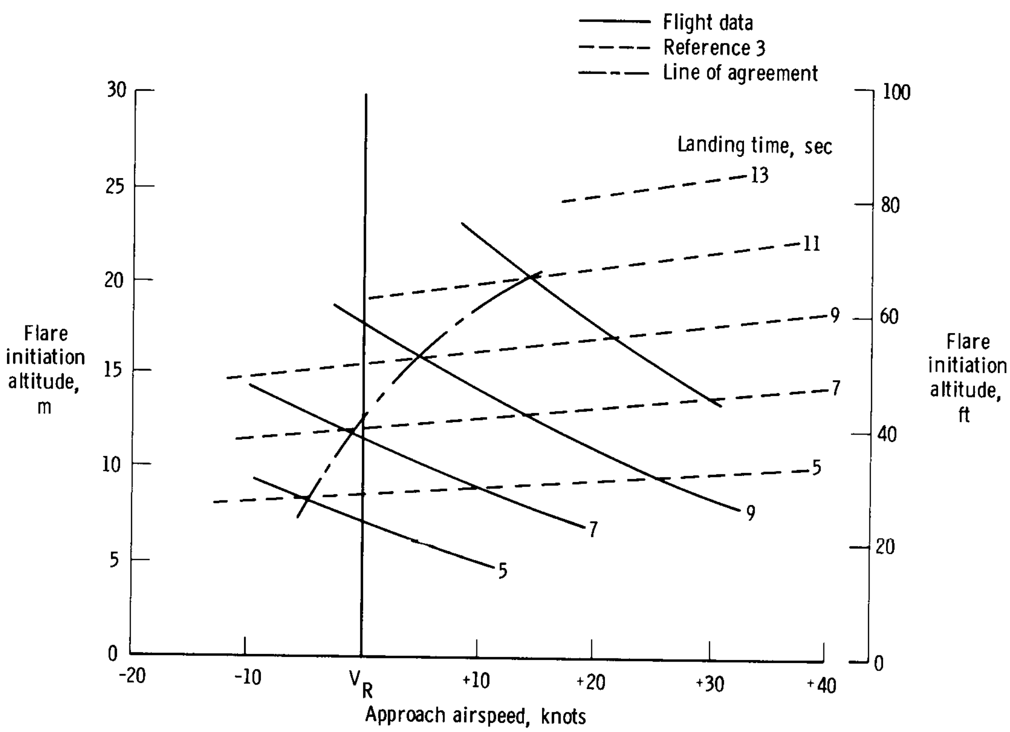


Figure 17. Comparison of landing time obtained from flight data with predictions from the model of reference 3. V_R = 135 knots.

Figure 18 compares the landing time obtained from flight data with the predictions from the model of reference 4. The model data agree with the flight data at slower airspeeds and higher altitudes than did the model data of reference 3. The time predicted from the model of reference 4 also shows a trend opposite to that of the flight data.

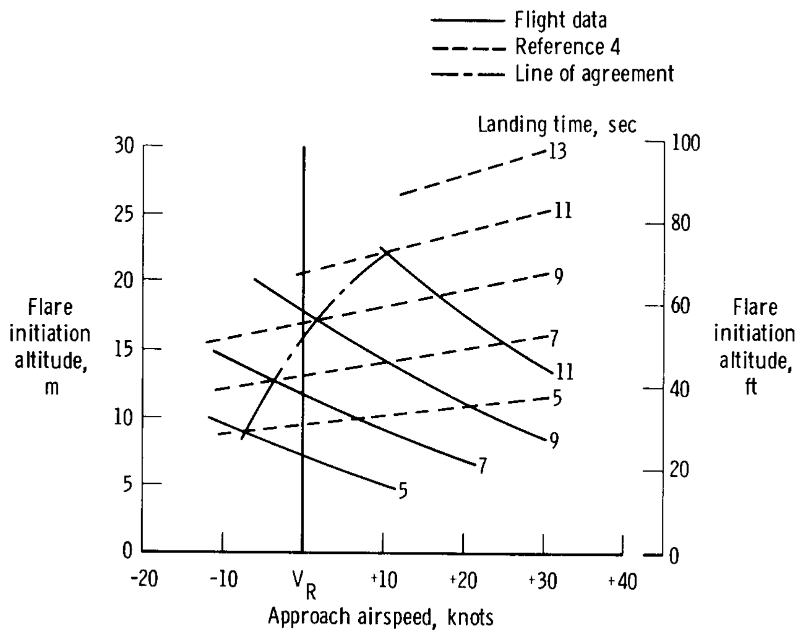


Figure 18. Comparison of the landing time obtained from flight data with predictions from the model of reference 4. V_R *= 135 knots.*

Figure 19 shows the relationship of the optimum flare window of figure 13 to the lines of agreement between the flight data and the models of references 3 and 4.

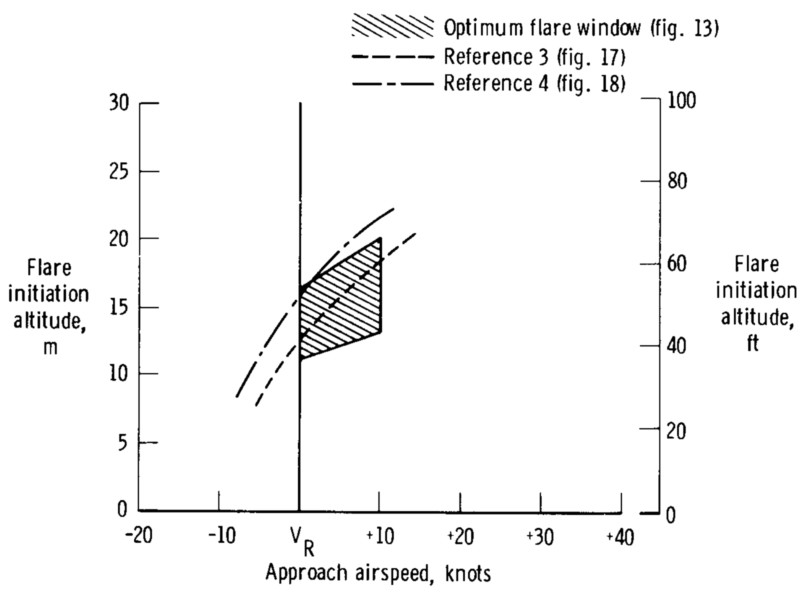


Figure 19. Relationship of the optimum flare window to the lines of agreement between flight and model data. V_R *= 135 knots.*

Considering the scatter of the flight data, both models satisfactorily predict the landing time near the optimum flare window when the landing maneuvers are similar to the typical transport landings upon which the models are based. Both models, however, predict landing times that are too long at slow airspeeds and too short at fast airspeeds.

The model of reference 5 was developed to provide a means of studying the problem of certifying landing distances and approach airspeeds. Application of this model to the test airplane yielded an indicated approach airspeed of 142 knots and a flare initiation altitude of 13.6 meters (44.6 feet). This prediction was based on a recommended flare acceleration of 1.06g and a float time of 5 seconds. In addition an approach glide slope of 3° and an altitude of 2.3 meters (7.5 feet) at the start of the float phase were assumed. Figure 20 shows the predicted approach airspeed and flare altitude to be in excellent agreement with the optimum flare window determined from the flight data. However, the total flare and float time computed for this model is 11.25 seconds in contrast to 9 seconds for flight data for the same conditions. This difference is believed to be caused by the relatively long model float phase of 5 seconds. This model is not readily applicable to nonoptimum approach conditions because there are no specific guidelines for making new assumptions for maximum normal acceleration, thrust management technique, altitude at the start of the float, or float duration.

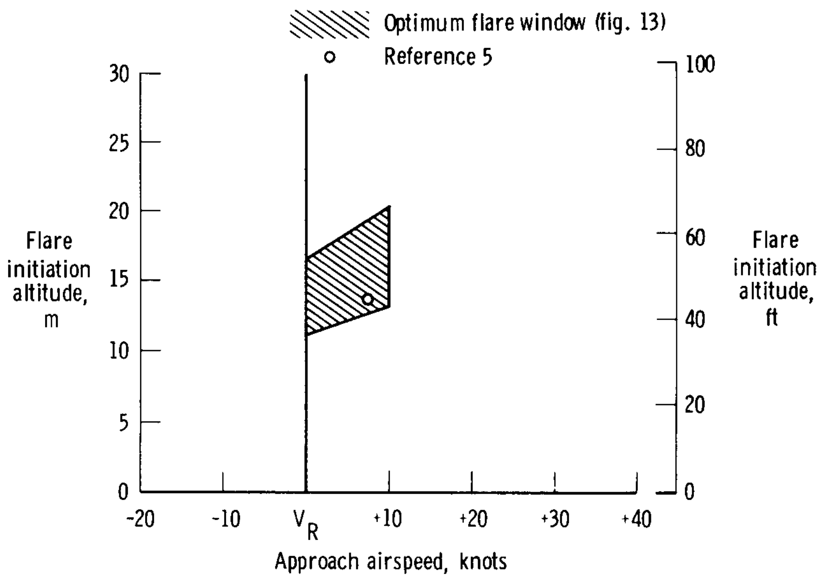


Figure 20. Comparison of the approach airspeed and flare initiation altitude predicted from the model of reference 5 with the optimum flare window. V_R = 135 knots.

Analytical Approximation of the Flight Data

Although the derivation of an analytical model for the landing task considered in this study is beyond the scope of this report, an analytical description of the landing time could be useful in developing such a model. The following equation is a linear approximation of the data of figure 8:

$$t_l = 0.4h_o + 0.1(V - V_R) + 2.0$$

Figure 21 compares the time derived from this equation with the faired lines from figure 8. This equation implies that the landing time increases 1 second for every 10-knot increase in speed margin and for every 2.5-meter increase in flare initiation altitude.

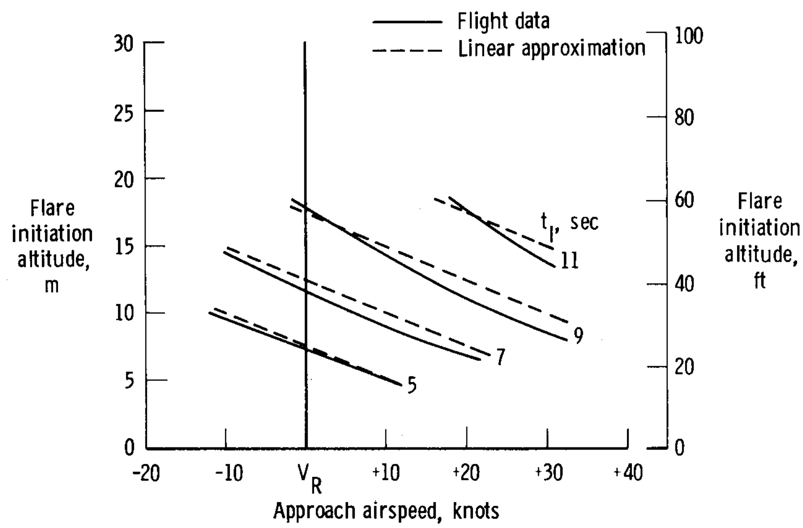


Figure 21. Comparison of the landing time obtained from flight with the linear approximation.

The following equation is a nonlinear approximation to the data of figure 8 and is compared with the data of figure 8 in figure 22:

$$t_1^2 = \frac{h_o + 0.155(V - V_R) - 2.73}{0.183 - 0.00185(V - V_R)}$$

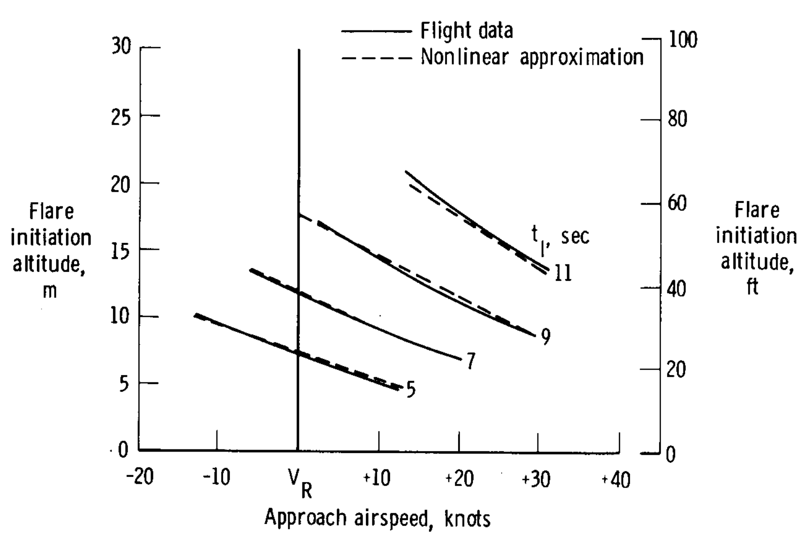


Figure 22. Comparison of the landing time obtained from flight with the nonlinear approximation.

Although no physical significance can be placed on the constants or the coefficients of the parameters, this expression implies that the total landing time is a square-root function of both the flare initiation altitude and the approach airspeed margin.

In an investigation into the relationship between airplane energy and the landing times obtained from this study, it was noted that the time curves of figure 8 are approximately parallel to lines of constant vertical specific energy (potential energy plus the vertical component of kinetic energy for a 3° approach angle). This comparison is shown in figure 23 in which V_R is assumed to be 135 knots.

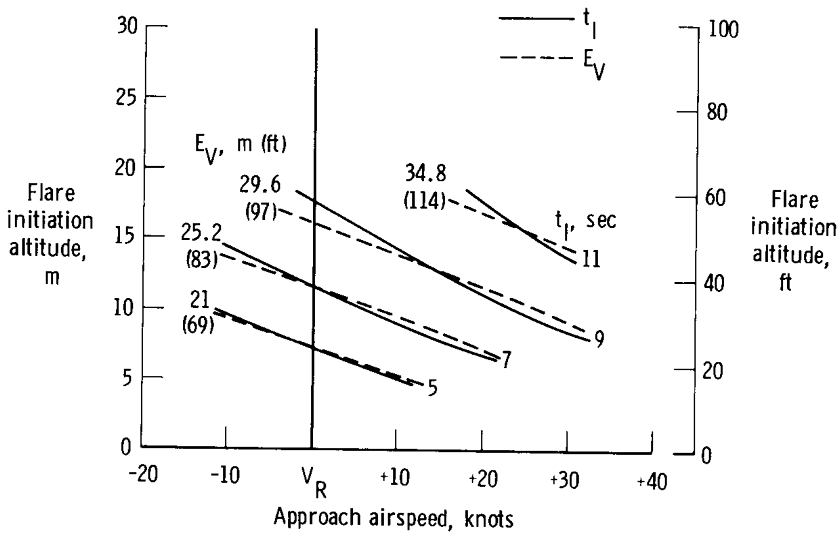


Figure 23. Comparison of landing time obtained from flight with the vertical component of total specific energy. $V_R = 135$ *knots.*

This limited study provides insufficient information from which to derive an analytical expression that can predict airplane flare altitudes and landing times. However, additional studies for other airspeeds and approach angles might provide enough information to make the derivation of a generalized equation possible.

CONCLUSIONS

A flight study was made to define the approach and landing characteristics of a typical subsonic transport airplane for wide ranges of approach airspeed and simulated breakout altitude and for two methods of thrust management. The results were compared with data from a simulator study and three analytical models. It was found that:

(1) The pilots' opinion of the acceptability of any breakout altitude was influenced more by the approach speed margin based on the reference airspeed (V_R) than by the absolute airspeed. The pilots' comments indicated that they were aware of the airplane's lack of energy when approaching at airspeeds slower than V_R and

the excess of energy when approaching at airspeeds greater than V_R + 10 knots.

(2) The optimum approach airspeed was V_R to V_R + 10 knots. The optimum flare initiation altitude range for unrestricted landings was from 11 meters to 20 meters (36 feet to 66 feet). The landing time in the optimum window was approximately 8 seconds.

(3) Approaches at airspeeds below V_R were characterized by limited pilot visibility, reduced control effectiveness, and low stall margins, and resulted in the hardest touchdowns and highest pilot workloads. The best flare for a slow approach was from an altitude of 9 meters to 14 meters (30 feet to 45 feet) with thrust maintained through touchdown and little or no float phase.

(4) Fast approaches (V_R + 20 knots to V_R + 30 knots) were characterized by a nose-down attitude which caused the sink rate to appear to be greater than it actually was and the danger of nosewheel-first touchdowns. The best flare for a fast approach was from an altitude of 15 meters to 27 meters (50 feet to 90 feet) with thrust reduced at flare initiation. This flare usually resulted in a relatively long float phase.

(5) Low-altitude flare performance required rapid control inputs and was greatly influenced by ground effect and residual longitudinal oscillations at flare initiation.

(6) A thrust cut at flare initiation was not a desirable technique for the test airplane because of an objectionable nose-down pitching moment associated with thrust reduction.

(7) The duration of the landing maneuver increased with increasing flare initiation altitude and with increasing approach airspeed margins above stall airspeed.

(8) Analytical models based on typical transport landing maneuvers did not predict the trend of the landing time increment as a function of approach airspeed margin based on V_R. The predicted times were too long at the slow approach airspeeds and too short at the fast approach airspeeds. This discrepancy is attributed to the different landing techniques used by the pilots for the various areas of the airspeed and altitude envelope.

Flight Research Center
National Aeronautics and Space Administration
Edwards, Calif., February 13, 1974

APPENDIX

PILOT COMMENTS

Typical pilot comments on the approach and landing maneuvers performed during the flight program discussed in this report are presented. The comments are preceded by the designation of the pilot (A, B, or C); approach airspeed with respect to reference airspeed (in knots); indicated approach airspeed (in knots); flare command altitude (in meters (feet)), and thrust management technique.

Slow Airspeed Characteristics

Pilot B; V_R - 10; 118; 15.2 (50); as desired.— It was a more difficult approach to fly. Quite a bit of work with power and quite a bit of power changing. A sink rate developed at the flare initiation, requiring an additional amount of power.

Pilot A; V_R - 10; 126; 15.2 (50); cut.— At about 60 meters (200 feet) [altitude] there seemed to be a strong settling tendency. I had to actually add power, but recovered to the proper approach angle and approach speed. At 15 meters (50 feet) I started my flare but did not come off with the power until approximately 6 meters (20 feet). I brought the power completely off and got a nice touchdown. I would say using that technique, leaving the power on after 15 meters (50 feet) even though the flare had started, the airplane did have plenty of flaring capability. I would not want to fly much slower on the final approach. I would say that the flaring capability would be in the neighborhood of 4.5 to 5. It's not very good in that it required a little extra technique. After touchdown it was quite noticeable how high the nose was and how low the tail was.

Pilot B; V_R - 5; 124; 15.2 (50); as desired.— The approach was more difficult to fly. There was a lot of power management required. At the flare the power was not touched at all. I did not feel that I had to add power, but I definitely felt that I had to carry the approach power until I'd stopped the rate of descent. I could also feel the ground effect. As soon as the aircraft stopped its sink rate, I pulled the power back slowly to idle and flared to the touchdown.

Pilot A; V_R - 5; 132; 15.2 (50); cut.— There is not an excess amount of flaring capability left in the airplane. We flared and touched a little bit hard, certainly harder than would be considered a nice landing. The reference [airspeed] minus 10 knots would probably require a slower retardation of the power. I would rate the flaring capability as about a 4.

Pilot B; V_R - 5; 127; 15.2 (50); cut.— The approach seemed to be flown real well as far as the flightpath and speed control. I would not want to be any higher [altitude] on the power cut. I would say we must have been around 12 meters (40 feet) for the flare. I did chop [power] at the flare light. I did a sort of special high-dip maneuver. I let the nose come down because I was a little higher [in altitude] than I wanted to be for that condition, and I rotated it in a more positive manner to stop the rate of sink for landing. It is a real undesirable technique. I'd rate down the arrestment of rate of sink capability. Call that about a 2.5, maybe a 3. You can rotate it, but it didn't stop the sink as well as you'd like. I had plenty of reaction time, but I think the altitude at the flare call was a little bit higher than I would like for the speed. That was about a 4.

Pilot B; V_R - 5; 118; 12.2 (40); cut.— Takes quite a bit of power adjustment to stay with it. It seemed like ample altitude to initiate the flare. I did not chop the power. I actually eased the power back as we approached the touchdown and made a power-on type of approach and landing. A rating of 3.5.

Pilot A; V_R - 5; 139; 6.1 (20); cut.— I chopped the power immediately and went right into the flare. The airplane flared nicely and touched down almost immediately. I would say that we just about have the end point at 6 meters (20 feet) elevation. I would not care to go to reference [airspeed] minus 10 for a 6 meter (20 foot) [altitude] flare because there is just not enough time to flare the airplane. Even though the airplane control response seems good, I suspect that it is a little less than it is at the higher speeds. I touched almost immediately as the flare was completed. I would rate the control response as about 2.5, but from the standpoint of the elevation I would say it's probably 6, because it certainly is approaching the absolute minimum altitude and time to flare.

Pilot A; V_R - 5; 140; 6.1 (20); cut.— There was more difficulty in holding the glide slope down the final approach due to the fact that more throttle and elevator motion were required to keep the speed as required. I flared and took off the power at the same time. I got good response from the elevator. It's too close to the ground to start your flare. A rating based on time and elevation available to rotate was 5.5.

Pilot B; V_R - 5; 135; 6.1 (20); cut.— It does require numerous power changes to keep the airspeed right on. I pulled the power back and had ample flare energy. Longitudinal response was adequate, and the flare capability was adequate; however, it was obvious that I was pretty close to minimum energy. I would not have wanted to pull the power any higher [in altitude]. A rating of 2.

Pilot B; V_R - 5; 134; 4.5 (15); cut.— As I waited for the light, it was obvious that we were going to be extremely close [in altitude]. When I got the light, I pulled back on the yoke and back on the power and I hit the runway shortly thereafter. It wasn't an extremely hard touchdown, but it was almost immediate on initiation of flare. The longitudinal response [rating] is still about a 2.5, and the task itself is a 5.5. It's not satisfactory at all; it was too close [in altitude], and there's really no reason to consider a situation like that.

Pilot B; V_R; 130; 24.4 (80); cut.— It appeared that I was fairly high [in altitude]. I chopped the power and made a sort of high-dip maneuver to get down to the runway with the energy to flare. The touchdown was pretty solid because I didn't have too much speed or time to fool around to set it on, once I had arrested the rate of descent. The altitude at power cut was too high for reference speed. The task of landing was rated a 4.

Pilot C; V_R; 131; 13.7 (45); as desired.— The flare height was too high; I had to delay 2 or 3 seconds before I initiated the flare. The power was cut after the initial rotation; [it] could have been cut prior to rotation without any problem.

Pilot C; V_R; 129; 9.1 (30); cut.— Flare height, I would say, was just right. It felt good. The rotation was smooth; the power cut was taken with the flare. It's the minimum satisfactory height. Any lower than that would have been rushing the pilot.

Pilot C; V_R; 130; 6.1 (20); as desired.— I cut the power right after the initial rotation. This induced a secondary elevator requirement which disturbed the airplane attitude.

Pilot A; V_R; 149; 6.1 (20); cut.— The rotation altitude of 6.1 meters (20 feet) was too low. I thought that I rotated and the airplane touched down almost simultaneously as the rotation was complete. We touched with a flatter attitude, a little more nose down, so it's quite obvious that the time and altitude to rotate is too small. From the standpoint of the distance and time available to rotate, the rating would be 5.5.

Pilot A; V_R; 148; 6.1 (20); cut.— I was watching out of the corner of my eye, and it appeared to me that we were approaching the ground at too rapid a rate. I initiated flare rapidly and chopped the power at the same time; it was actually initiated just prior to the light. The elevator response was excellent. I made a large input to the elevator to flare, and the airplane responded very well. I think we were definitely flaring too late, almost dangerously late. I would rate the control response as about a 2, but the flare altitude probably in the neighborhhod of a 6.

Intermediate Airspeed Characteristics

Pilot A; V_R + 10; 134; 24.4 (80); cut.— I had the feeling that we were fairly high [in altitude]. When the light came on, I chopped the power, knowing that we had reference [airspeed] plus 10. I felt we were so high [in altitude] it might be a problem. I was a little more careful in my flare to make sure that I didn't settle in hard, and I actually held it off a little bit. There certainly was that feeling that we were high. I would rate the entire maneuver as a 3: satisfactory, but noticeably higher than I would like to start my flare.

Pilot B; V_R + 10; 147; 21.3 (70); as desired.— It [the thrust] did not go completely to idle because of the altitude. It [the altitude] did seem just a little bit high for a normal flare, and the approach did continue a little closer to the runway. Longitudinal control and handling are considered very good—a rating of 2. I would rate the flare altitude as just a little bit high for that speed.

Pilot B; V_R + 10; 144; 12.2 (40); as desired.— It seemed like it [the altitude] may have been a little bit low for flare when I first looked up, but once I actually started the flare maneuver at 12.2 meters (40 feet), there was ample energy and distance for the flare maneuver and there was ample speed. The power was pulled to idle almost immediately on initiating the flare. There was no problem at all arresting the rate of descent for the landing. Longitudinal qualities were good.

Pilot A; V_R + 10; 132; 12.2 (40); cut.— It felt like it was just at the right altitude to flare. Although I did get a fairly solid touchdown, I felt that it was the right altitude to flare. The initiation of the flare did not seem excessively high.

Pilot A; V_R + 10; 163; 9.1 (30); cut.— I had the feeling that we were actually getting a little bit low [in altitude] to start the flare. I would rate the maneuver as a 3. You feel a little uncomfortable, but the airplane response was excellent.

Pilot A; V_R + 10; 156; 7.6 (25); cut.— It was obvious to me that the flare was a low one [in altitude]. It was certainly lower than I would want to do, and if it were any lower it would probably be a little dangerous. It was just barely acceptable.

Pilot B; V_R+ 10; 152; 6.1 (20); cut.— I was getting on the close side [in altitude], and my desire to arrest the sink rate resulted in a balloon type of maneuver. It's an uncomfortable one, and the rapid closure hurried me as far as that initial flare input. A rating of 3.

Pilot B; V_R + 10; 153; 6.1 (20); as desired.— I purposely watched out the side of the cockpit more, out of concern from the previous approach, and it was interesting to note the difference between coming off the instruments for the previous approach at 9 meters (30 feet), looking up and being sort of surprised at the proximity to the ground, and the closure rate as compared with this one. I was actually looking out from 15 meters (50 feet) on down. Coming off the gages and looking up is a very abrupt change. If you've been able to see the runway from 15 meters (50 feet) or so down, it doesn't worry you so much because you're up with the situation.

Pilot B; V_R + 10; 153; 3.0 (10); as desired.— This altitude is too low, even eyeballing out the window. It gets to the point where I'm not sure that I can estimate that 3 meters (10 feet) well enough to know where the gear is. I looked up, and I'm not sure that my gear hadn't hit about then. I think that pilots vary, but in that last 1.5 meters (5 feet) most guys guess where the gear is, and now we're trying to flare in that area, and it's not good.

Fast Airspeed Characteristics

Pilot A; V_R + 20; 144; 15.2 (50); cut.— I had the feeling that we were moderately close to the runway. When the light came on, I chopped the power and initiated the flare and held it off a little. I had the feeling I was a little fast, but not as noticeable as those previous runs where we used the plus 30 knots. Seemed like we got a little bit of ground effect prior to the flare, which cut down on our rate of descent.

Pilot B; V_R + 30; 153; 21.3 (70); cut.— Handling qualities are good. As I came up visual and looked out, I had the feeling that there was no reason to hurry the flare. The approach was just faster than heck, and a lot of energy and a lot of runway were used up trying to get the aircraft on the runway. The speed and energy are too high.

Pilot C; V_R + 30; 176; 18.3 (60); cut.— The altitude was on the high side, but very little. I could have been a little bit lower, not over 3 meters (10 feet), though. A little more float than I would have liked.

Pilot B; V_R + 30; 162; 15.2 (50); as desired.— Just excessive speed. The power was stopped immediately at the 15.2-meter (50-foot) call. The aircraft was held just about level [in altitude] as the speed bled off, then gradually eased down to a touchdown. Really not a comfortable approach. A lot of time to make the touchdown but very uncomfortable.

Pilot A; V_R + 30; 168; 15.2 (50); cut.— There is an excess amount of energy there. I would say that the elevator flaring quality was 1.5. The overall rating would be a 4 because of the excessive amount of energy causing the airplane to float.

Pilot A; V_R + 30; 154; 15.2 (50); cut.— I feel that I was quite close to the ground at the flare command. I would have liked to have started the flare just a slight bit earlier, so I would rate the maneuver as a 3.5.

Pilot B; V_R + 30; 172; 12.1 (40); as desired.— At 12.1 meters (40 feet) you seem like you're closing on the ground rapidly as you glance up. You're so fast and have so much energy that just a little bit of elevator arrests your closure, and then you're faced with the long speed bleed off prior to touchdown. This is just an uncomfortable type of approach to landing.

Pilot A; V_R + 20; 140; 10.7 (35); cut.— It appeared to me we were quite close to the ground. I may have started my flare a fraction of a second before the light came on. It was a natural reaction because it seemed to me that the flare needed to be started, and I chopped the power and flared, and I think it was obvious that it was a little closer to the ground than I would like. I would rate that as a 4.5.

Pilot C; V_R + 30; 174; 12.2 (30); cut.— It appeared that I was getting too low [in altitude], and I had to hold off the urge to start my flare; however, I did make the throttle cut and flare at the light. It was definitely too low for that condition. The response was very good, and we got a more-or-less step input in attitude and slowed up the rate of descent.

Pilot B; V_R + 20; 153; 7.6 (25); cut.— The approach was real nice and smooth—on glide path all the way. The time between the visual call and the light seemed like a long time. This was another low [altitude] one. I don't care for the altitude.

It is a little bit too close for me to come from instrument conditions to another reference and try to accommodate at that point.

Pilot B; V_R + 30; 166; 3.0 (10); as desired.— I ballooned, because when I glanced down and started to flare I was so close that I just reefed it in, and with that extra speed I ballooned back up again and that didn't really surprise me a lot. I wasn't pleased with it, but I'd rather have done that than hit the ground. That's just pressing it in too close, and it's too difficult to make a smooth flare with that energy. You want to be on that side rather than misjudging it and hitting the ground prematurely.

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